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THE EFFECT OF MODEL SCALE ON RIGID-BODY UNSTEADY PRESSURES ASSOCIATED WITH BUFFETING

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By Charles F. Coe

National Aeronautics and Space Administration
Ames Research Center
Moffett Field, Calif.

ABSTRACT

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The question of the effect of model scale on launch vehicle dynamic measurements is one which invariably arises in connection with the application of measured unsteady pressures on wind-tunnel models. The scaling of unsteady pressure measurements is discussed in this paper which presents comparisons of results of pressure-fluctuation measurements on both wind-tunnel models and on full-scale Ranger 5 and Mercury vehicles. In addition, results of tests using different sized models are shown in order to cover some of the different types of local flow associated with buffeting. The effects of scale on the root-mean-square fluctuations of pressure, the longitudinal correlation of the fluctuations, and on the power spectral densities are shown for selected transonic Mach numbers where the fluctuations are most severe. Conf

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LIST OF ILLUSTRATIONS

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INTRODUCTION

The unsteady aerodynamic loads on launch vehicles at transonic speeds have recently received considerable attention. These unsteady loads result from pressure fluctuations that occur within regions of shock waves or regions of separated flow or both. Escape rocket systems, blunt noses to insure abort stability, bulbous payloads which are larger than their booster rockets, and numerous protuberances all lead to this troublesome flow unsteadiness which can cause buffeting.

Several wind-tunnel investigations (refs. 1 to 6) have been undertaken at Ames and Langley Research Centers and at Arnold Engineering Development Center to measure pressure fluctuations on both specific configurations and also on a variety of body shapes to determine effects of profile variations. When any of these pressure-fluctuation measurements are used for estimation of vehicle dynamic response, questions invariably arise as to the proper method of scaling the data to full scale. For example, are the concepts of a constant Strouhal number and scaling by application of the commonly used reduced frequency parameter, $\omega d/V$, appropriate for random nonperiodic buffet pressures. For lack of any verifying information the above concepts have been employed in references 6 and 7. Two recent investigations (refs. 8 and 9) have devoted some attention to the problem of scaling unsteady pressures. The latter (ref. 9), which contains data for models varying in size by a ratio of 5 to 1, tends to substantiate the validity of the reduced frequency parameter for scaling.* The ultimate test of scaling buffet pressures, however, comes with the direct comparison between wind-tunnel model data and full-scale data obtained during the launching of a vehicle.

The measurement of differential pressure fluctuations at two Agena stations during the Ranger 5 launch and of pressure fluctuations on the Mercury-Atlas adapter during launch of the MA-4, MA-5, MA-7, and MA-8 provided a good opportunity to make such comparisons. As a result, tests of a 7-percent scale Mercury model and a 10-percent scale Ranger model were included in an investigation of scale effects using different sized models which was in progress at Ames Research Center. The tests were conducted at transonic Mach numbers with

*Results from this investigation appear in the paper by Hanson and Jones of Langley presented at an earlier session of this Symposium.

pressure transducers located at the same stations as the full-scale flight instrumentation. It is primarily the results of these comparative tests that are contained herein. Additional data from the general research program are included to illustrate the effects of scale for different types of unsteady flow.

NOTATION

d	body reference diameter
D_{max}	maximum body diameter
f	frequency, cps
M	free-stream Mach number
p_t	stagnation pressure
q_o	free-stream dynamic pressure
V	free-stream velocity
x	distance along body axis from nose
α	angle of attack
Φ	power spectral density of fluctuating pressure coefficient, $\overline{\Delta C_p^2}$ per cps
φ	power spectral density of fluctuating pressure, $\overline{\Delta P^2}$ per cps
ω	frequency, radians per second
$\Delta C_p(RMS)$	coefficient of the root-mean-square fluctuation of pressure about the mean, $\frac{\Delta P(RMS)}{q_o}$
$\overline{\Delta C_p^2}$	coefficient of the mean-square fluctuation of pressure, $\frac{\overline{\Delta P^2}}{q_o^2}$
$\Delta P(RMS)$	fluctuation of pressure about the mean
$\overline{\Delta P^2}$	mean-square fluctuation of pressure, psf^2

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MODELS

The models tested to investigate scaling effects (fig. 1) were a 7-percent scale Mercury-Atlas, a 10-percent scale Ranger, and three sizes each of models 8 and 13a.* For the Mercury-Atlas and Ranger models the Atlas cylindrical bodies were neither scaled in length nor did they include any protuberances. Key longitudinal stations are indicated in the figure to aid in visualizing the placement of the pressure transducers relative to the body profiles. The reference diameters used for scaling the results are also shown.

All the models were sting mounted except the 26-inch-diameter model 13a which was tested as a half model mounted on the 14-foot transonic wind tunnel wall to minimize the effects of blockage. All the models were tested in the 14-foot wind tunnel except the Mercury-Atlas which was tested in the 11-foot transonic wind tunnel and the 6.31-inch-diameter model 8 which was tested in the 6- by 6-foot wind tunnel.

The pressure transducer stations that match the locations on the full-scale vehicles are marked with an x in figure 1. The differential pressure fluctuations were measured on the Ranger by taking the electrical difference between the outputs from the transducers mounted opposite each other. Flush-mounted 1/4-inch-diameter strain-gage-type transducers were used on all the models.

A photograph of the Mercury model in the 11- by 11-foot wind tunnel is shown in figure 2. An arrow indicates the relative location of the transducer with respect to the bulges on the ring clamp between the spacecraft and adapter section. The transducer station behind one of the bulges at approximately mid-length of the adapter is that at which flight data were obtained.

EFFECTS OF SCALE

When dynamic data associated with motion effects are measured on models, it is accepted that the geometric similarity of the flow cannot be maintained unless the reduced frequencies for model and full scale are the same. Although there has been doubt whether the reduced frequency parameter is applicable to random unsteady aerodynamic measurements, simple dimensional analyses by Liepmann (ref. 10) of the variable parameters involved indicate that the dimensionless reduced frequency parameter can be used to scale pressure-fluctuation measurements:

$$\frac{\omega d_1}{V_1} = \frac{\omega d_2}{V_2}$$

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*The model numbers were assigned to the series of launch vehicle payload shapes tested at Ames Research Center.

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and

$$\Phi_1 = \frac{\overline{\Delta C_{p_1}^2} V_1}{d_1} = \frac{\overline{\Delta C_{p_2}^2} V_2}{d_2} = \Phi_2$$

Since

$$\Delta C_p(\mathrm{RMS}) = \sqrt{\int_{(\omega d/V)_1}^{(\omega d/V)_2} \left(\frac{\Phi V}{2\pi d}\right) d\left(\frac{\omega d}{V}\right)}$$

it follows that in order to compare RMS measurements from model to full scale or from one model size to another, the range of frequencies included in the RMS measurements must be scaled in proportion to the reference dimensions.

Comparisons of Mercury Results

A comparison of power spectra of the pressure fluctuations measured on the Mercury-Atlas adapter is shown in figure 3. The wind-tunnel data are for a fixed Mach number of 1.0 while the flight data were obtained for a range of Mach numbers near 1.* The comparison is based on reduced frequency. (The $V/2\pi d$ in the ordinate scale converts the power spectra from $\overline{\Delta C_p^2}$ per cps to $\overline{\Delta C_p^2}$ per unit of reduced frequency.) It can be seen from these results that the 7-percent model data, which have been scaled by a factor of about 14.3, fit reasonably well within the limits of the spread of flight measurements. To illustrate the extent of frequency scaling the limit of the 7-percent model data is at approximately 5,200 cps while the full-scale data for the same reduced frequency is approximately 365 cps.

A curve is also shown from reference 6. While this curve appears higher than the others, the difference between it and MA-4 levels is less than the spread from MA-4 to MA-5. This spread of a factor of about 4 on a mean-square scale (factor of 2 on a RMS scale) serves to indicate the limits of accuracy, within the current state of the art, that might be expected when predicting pressure fluctuations from model measurements. One obvious factor that influences the accuracy of flight data is the fact that flight-time histories are not stationary.

Since the RMS level of amplitude is the most common measurement applied to pressure fluctuations, it is appropriate to examine the effects of scaling on these measurements. The flight-time histories of the RMS pressure fluctuations on the Mercury-Atlas adapter are shown in figure 4. Points from the 7-percent scale model extend over a range of Mach numbers from 0.8 to 1.2. Since there were differences between model q_o and full-scale q_o, the model results have been adjusted to full scale. As noted, the band-pass frequency range of the flight data extends up to 500 cps. The scaled frequency range of

*The full-scale data were obtained from unpublished results which have been compiled by Mr. James Ancell of Aerospace Corporation.

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the model should extend to about 7,200 cps, but unfortunately the upper frequency limit of the tape recording of data was only 6,000 cps. Even though the band-pass range was less than the properly scaled range, these 7-percent model data still generally are close to the MA-5 data. The point indicated by an x shows an estimated level for the range of frequencies extrapolated to 7,200 cps from the power spectrum in figure 3. As can be seen, the agreement between the 7-percent model data and the average flight data is improved. Points are also shown in figure 4 which were obtained for a band-pass filter range from 8 to 500 cps which is about the same range as for the full-scale data. The difference between the comparisons of model results and flight data for the two filter ranges further substantiates the validity of frequency scaling.

Comparisons of Ranger 5 Results

The power spectra of differential pressure fluctuations on the Agena with the Ranger 5 payload are shown in figure 5.* These results, which were scaled by a factor of about 10, generally agree more closely than did the Mercury data, and consequently add more support to the validity of scaling by the reduced frequency parameter. It should be noted that the frequency range of the measurements of fluctuations on the Agena was very low compared to the range available on the Mercury. This fact may partly account for the better comparisons between the Agena measurements.

Time histories of the RMS levels of the differential pressure fluctuations are shown in figure 6. As with the Mercury data, the range of band-pass filtering of the signal going into the RMS meter was scaled inversely as the model scale. For the Agena the range was from 8 to 1,000 cps for the model and from 0.8 to 100 cps for full scale. With these band-pass frequencies precisely scaled, the maximum intensities were reasonably well predicted as was the variation with time for station 259. At station 249 the flight-time history indicates an earlier buildup of intensity and also a dip near 47 seconds that was not followed by the wind-tunnel data which were taken at fixed Mach numbers. One might speculate that these differences between wind-tunnel and flight data could well be within the limits of accuracy that can be expected considering the unknown effects of Reynolds number and also other problems associated with obtaining accurate dynamic measurements.

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*The flight power spectra and a magnetic tape of the differential pressure fluctuations were obtained from Lockheed Missiles and Space Company. The flight data will appear in a forthcoming report by William Henricks, Flight Test Report for Ranger Vehicle 6005, SS/626/5351, LMSC/A384258.

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Effects of Scale on Model 8

The separated flow on the Mercury adapter and on the Agena both produced relatively flat power spectral densities. Previous experience with model 8 for other investigations has shown that the spectral densities vary in shape from a predominately low-frequency spectrum near the maximum diameter shoulder to a flat spectrum as the distance from this shoulder is increased. For this reason model 8 was originally selected for the investigation of scale effects so that more than one spectrum shape could be covered.

Figure 7 shows the longitudinal distribution of pressure fluctuations on model 8 for three different model sizes. As was done previously the band-pass frequencies for the RMS readings were scaled inversely as the model diameter starting from an upper limit of 2,000 cps on the 6.31-inch-diameter model. Once again it appears that satisfactory agreement was obtained, further substantiating the use of the reduced frequency for scaling. This substantiation by use of the RMS levels is only valid, however, where the power spectral levels are high enough in the frequency range being scaled to effect the RMS. For model 8 the power spectra indicate higher energy levels at the higher frequencies at stations aft of $x/D_{max} = 1.4$.

As previously mentioned, near the shoulder on model 8 the pressure fluctuations are concentrated at the lower frequencies. An example of scaled power spectra from a station within this region is shown in figure 8. The results appear to scale well including the peaks at $\omega d/V = 0.78$, which, as a result of the satisfactory scaling, can be concluded to be a peak caused by an aerodynamic frequency rather than a model motion. It is also interesting to note that the results were obtained in different wind tunnels. The 6.31-inch model was tested in the 6- by 6-foot tunnel and the other two models were tested in the 14-foot wind tunnel.

Effects of Scale on Model 13a

All the previous data shown lead to the conclusion that pressure-fluctuation measurements should be scaled by application of the reduced frequency parameter. These data have been from regions of separated flow, and the spectra have been smooth curves except for the peaks which scaled on model 8. In contrast to the previous smooth spectra, figure 9 shows an example of power spectra of fluctuations in the region of the shock wave on model 13a. These results have not been scaled. It can be noted that several peaks coincide on the two smaller models which were sting mounted, and that a smoother spectrum without such predominant peaks was measured on the 26-inch-diameter half model which was mounted on the tunnel wall. The fact that the peaks tend to coincide when the model supports are similar and change when the support is changed indicates that the shock-wave motion is influenced by model motions. The peak near 190 cps also coincides with a stream disturbance in the 14-foot wind tunnel (see ref. 1) thus indicating an influence of stream fluctuations as well. Since it would be expected that the full-scale fluctuations would also be influenced by vehicle motions and stream fluctuations, the details of spectra of this type certainly could not

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be scaled. It appears, at present, that for design purposes the best approach would be to construct a smooth power spectrum having a slope like the over-all slope of the measured curve and an area under the curve equal to the measured mean-square amplitude. There is some justification for this approach since as shown in reference 1 a model in different wind tunnels with different support properties produced the same RMS measurements even though in one case a large peak predominated. In other words, it appears that the energy available from the shock wave to produce fluctuations is unchanged, but that the frequency distribution can be influenced.

Effect of Total Pressure Variations

The power spectra of the pressure fluctuations have been put in coefficient form by dividing the spectra measurements by q_o^2. While generally this has been assumed to be a correct approach, nevertheless, some measurements were made on model 8 to check the effect of varying q_o by testing at different total pressures. Figure 10 shows an example of power-spectrum measurements of differential pressure fluctuations obtained in the 11- by 11-foot transonic wind tunnel at total pressures of from 15 to 60 inches of mercury. As can be seen there was little effect of total pressure.

Correlation of Pressure Fluctuations

In order for wind-tunnel measurements of pressure fluctuations to be of value it is necessary that the spatial correlation of the fluctuations on the model be the same as on the full-scale vehicle. There has been insufficient time to obtain cross spectral densities of any of the scaling data before this symposium; however, a quick look at the over-all correlation was obtained from correlation coefficient measurements as shown in figure 11. As with the RMS values previously presented, the band-pass frequency range of the signals to the analyzer was scaled inversely as the model diameters. While there are not many points available for comparison, those shown indicate the same correlation coefficients for a difference in model size near a factor of 4. Other correlation coefficient measurements with respect to different stations show essentially the same agreement for the same two models.

Attempts were also made to perform a correlation coefficient analysis between the two stations tested on the Ranger. Average coefficients obtained from the flight data over the periods of time from 43 to 46 seconds after launch and from 45 to 50 seconds agree reasonably well with the 10-percent scale model data at fixed Mach numbers of 0.79 and 0.90, respectively. The corresponding measurements were as follows:

Full scale, 43-46 sec	correlation coefficient = 0.155
10-percent model, M = 0.79	correlation coefficient = 0.130
Full scale, 40-45 sec	correlation coefficient = 0.180
10-percent model, M = 0.90	correlation coefficient = 0.21

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CONCLUDING REMARKS

On the basis of this investigation and results presented herein, it appears that pressure-fluctuation measurements on models in regions of separated flow should be scaled to full scale by application of the reduced frequency parameter. Scaling by a factor of 14.3 on the Mercury model and by a factor of 10 on the Ranger 5 model gave good agreement with flight results.

In the region of the shock wave, model measurements can be influenced by motions of the model and also by disturbances in the stream. As a result, less accuracy can be expected. It will probably be necessary to estimate power spectral densities from the measured RMS level and a generalized spectrum shape.

Correlation coefficient measurements indicate the same coefficients for different sized models of model 8. Reasonable agreement was also obtained between the 10-percent model of the Ranger 5 and full scale; however, cross spectral densities are required before definite conclusions can be drawn regarding possible effects of scale on the spatial correlation of pressure fluctuations.

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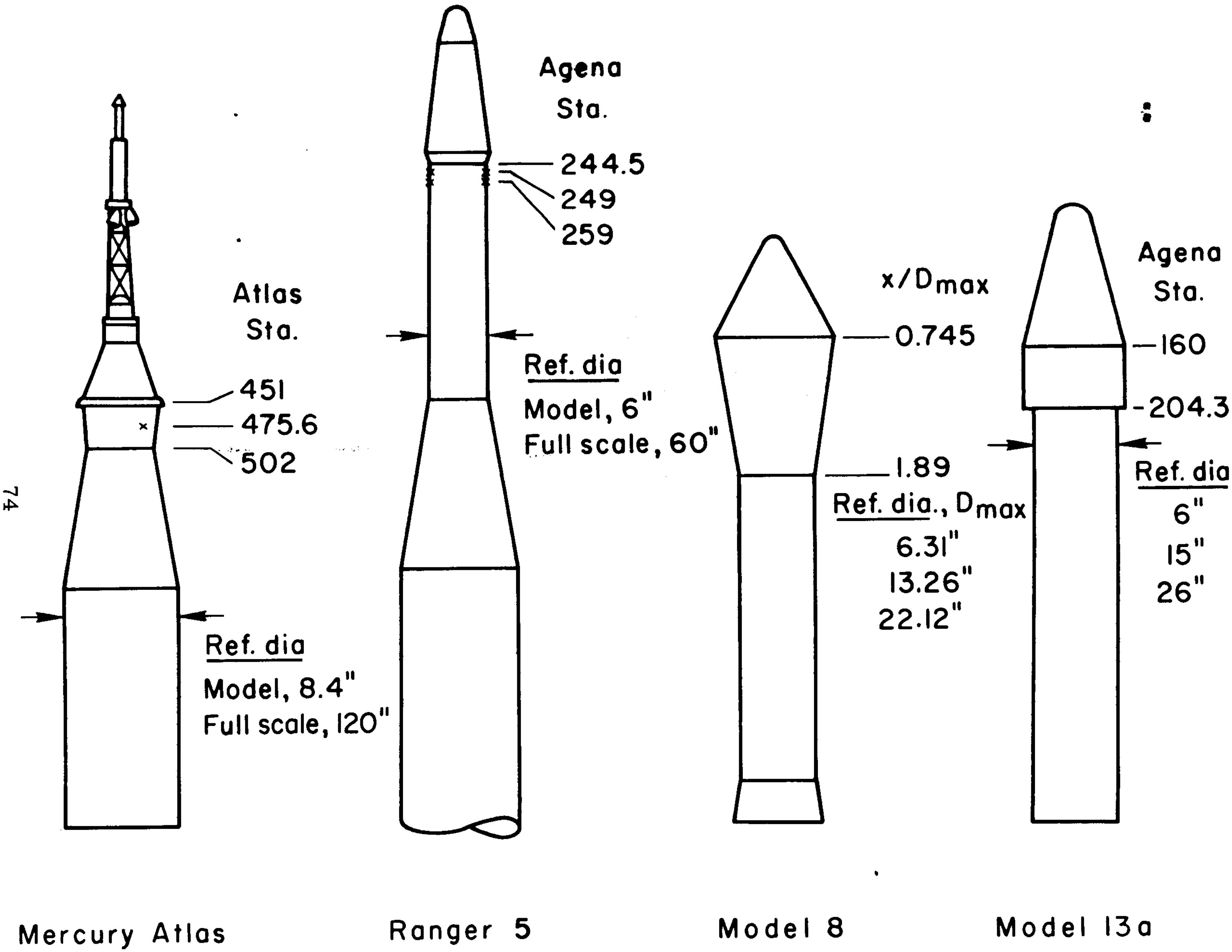

Figure 1.- Models investigated for scale effects.

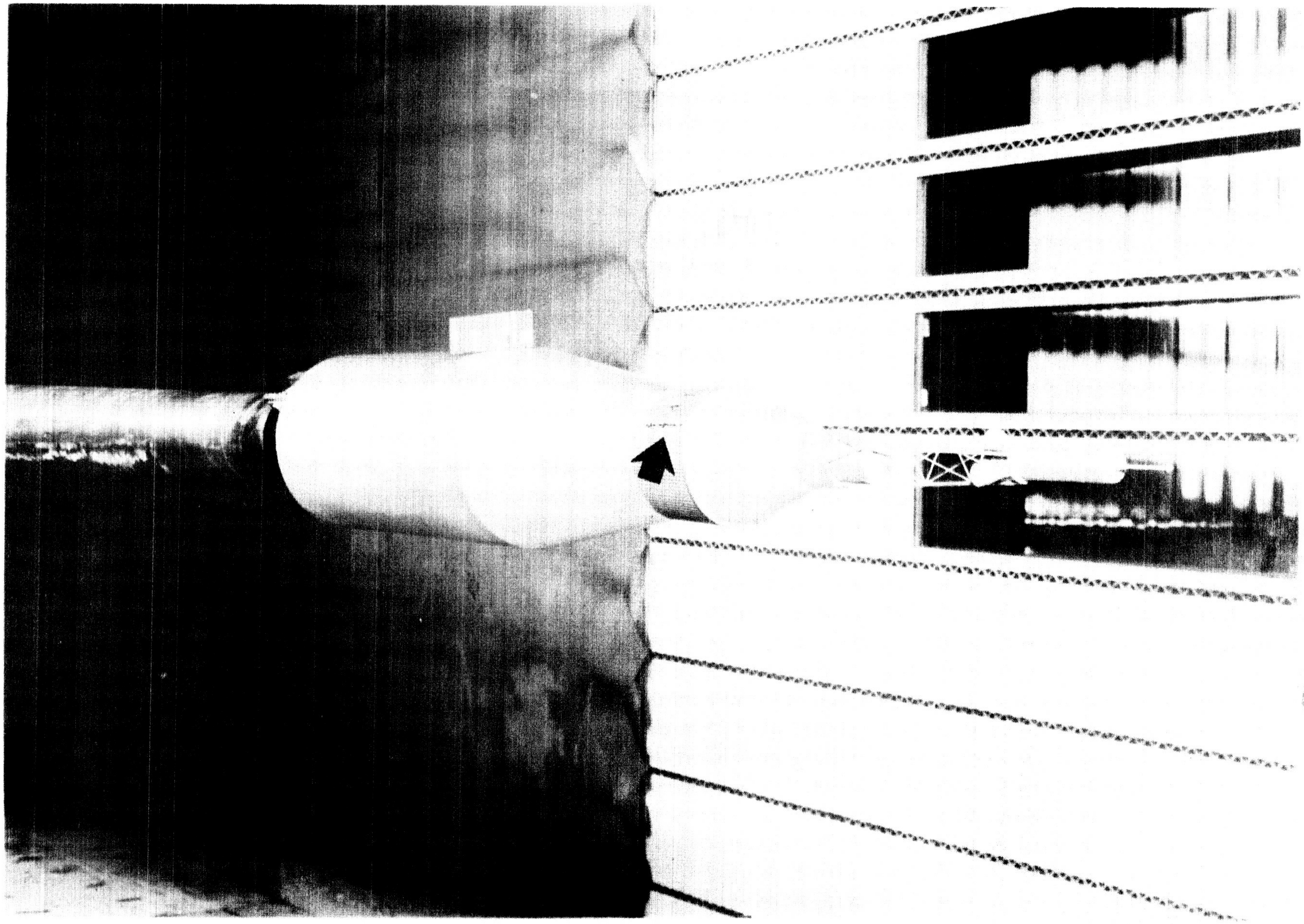

Figure 2.- Photograph of 7-percent scale Mercury model.

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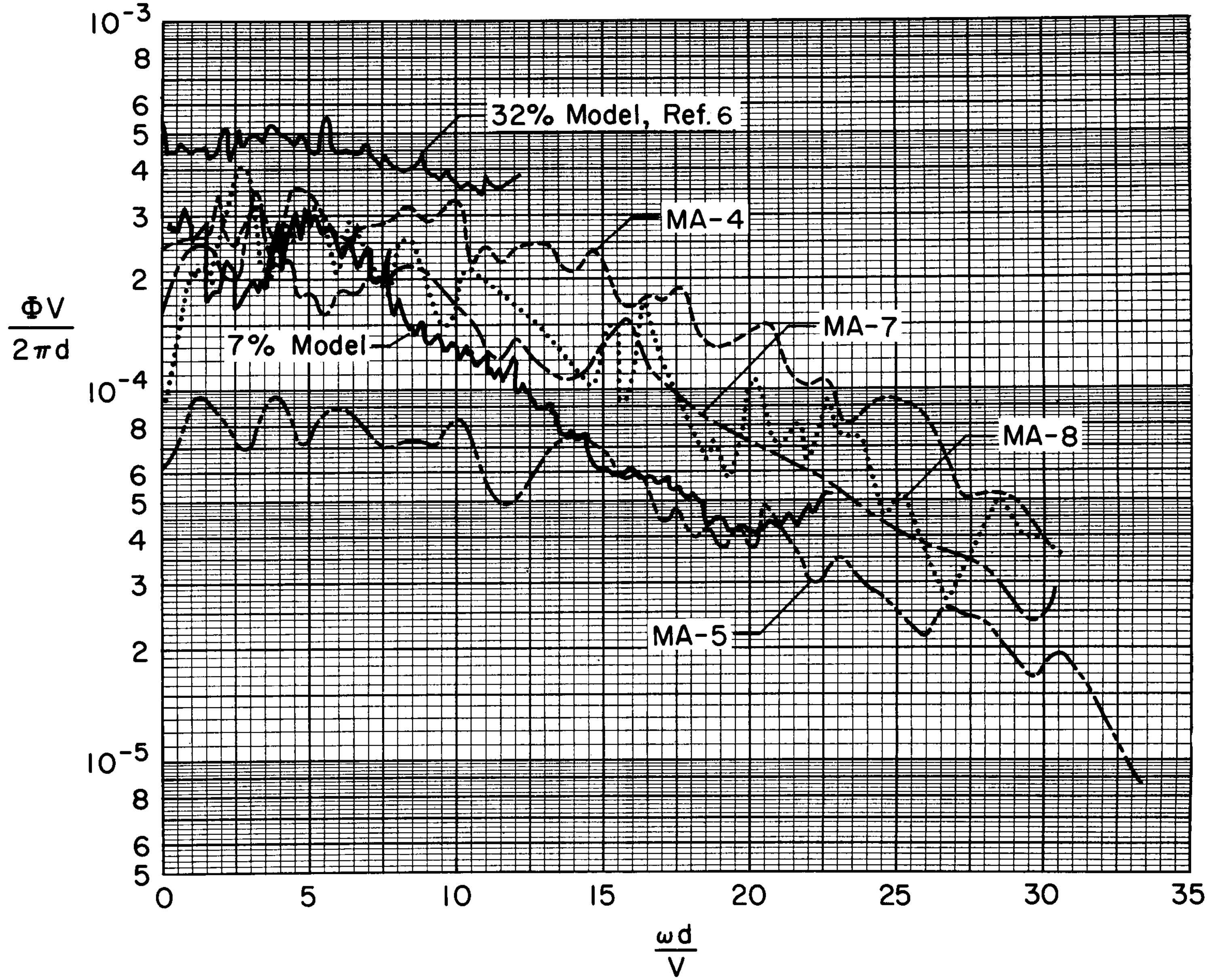

Figure 3.- Power spectra of pressure fluctuations on the Mercury-Atlas adapter near M = 1.

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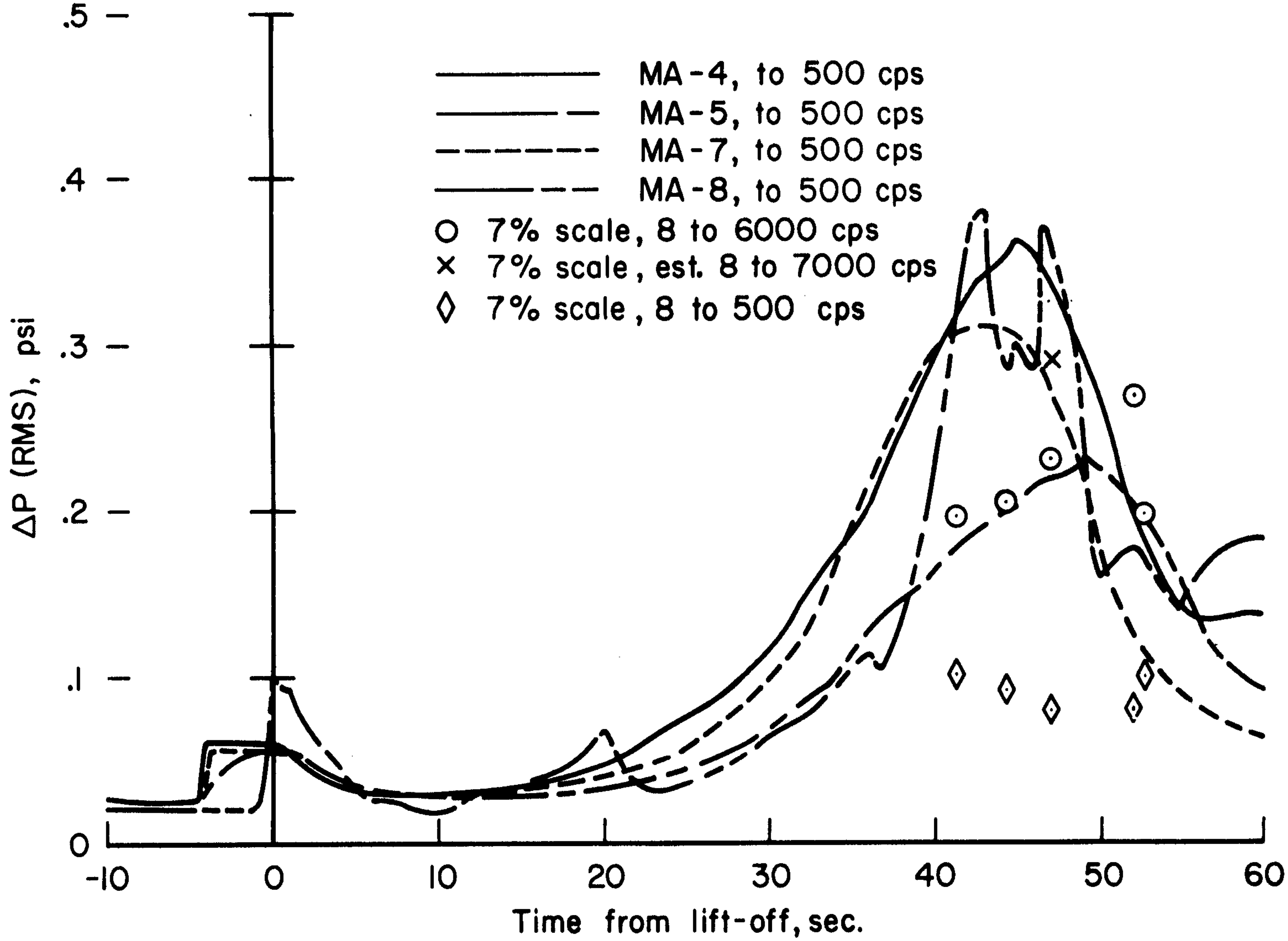
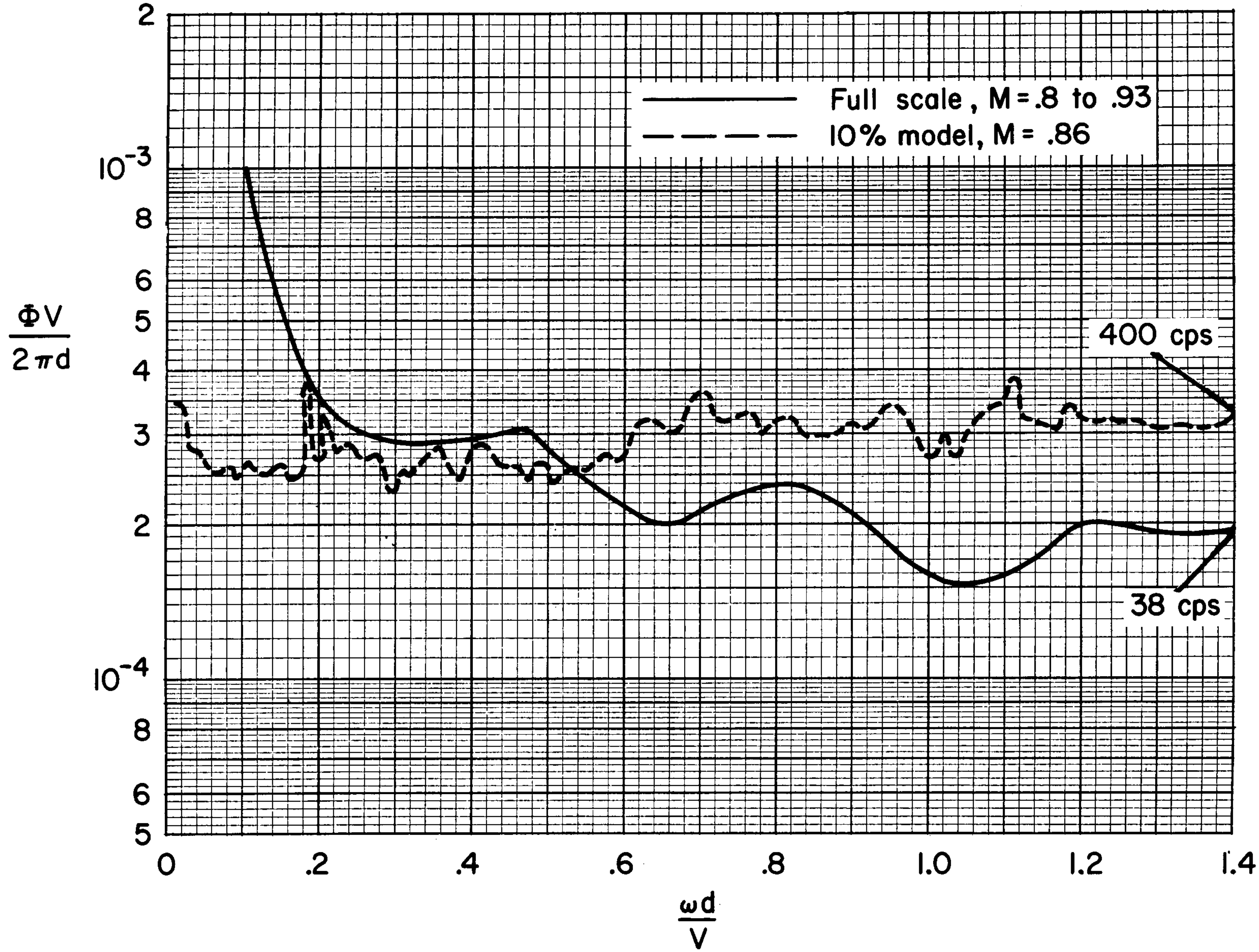
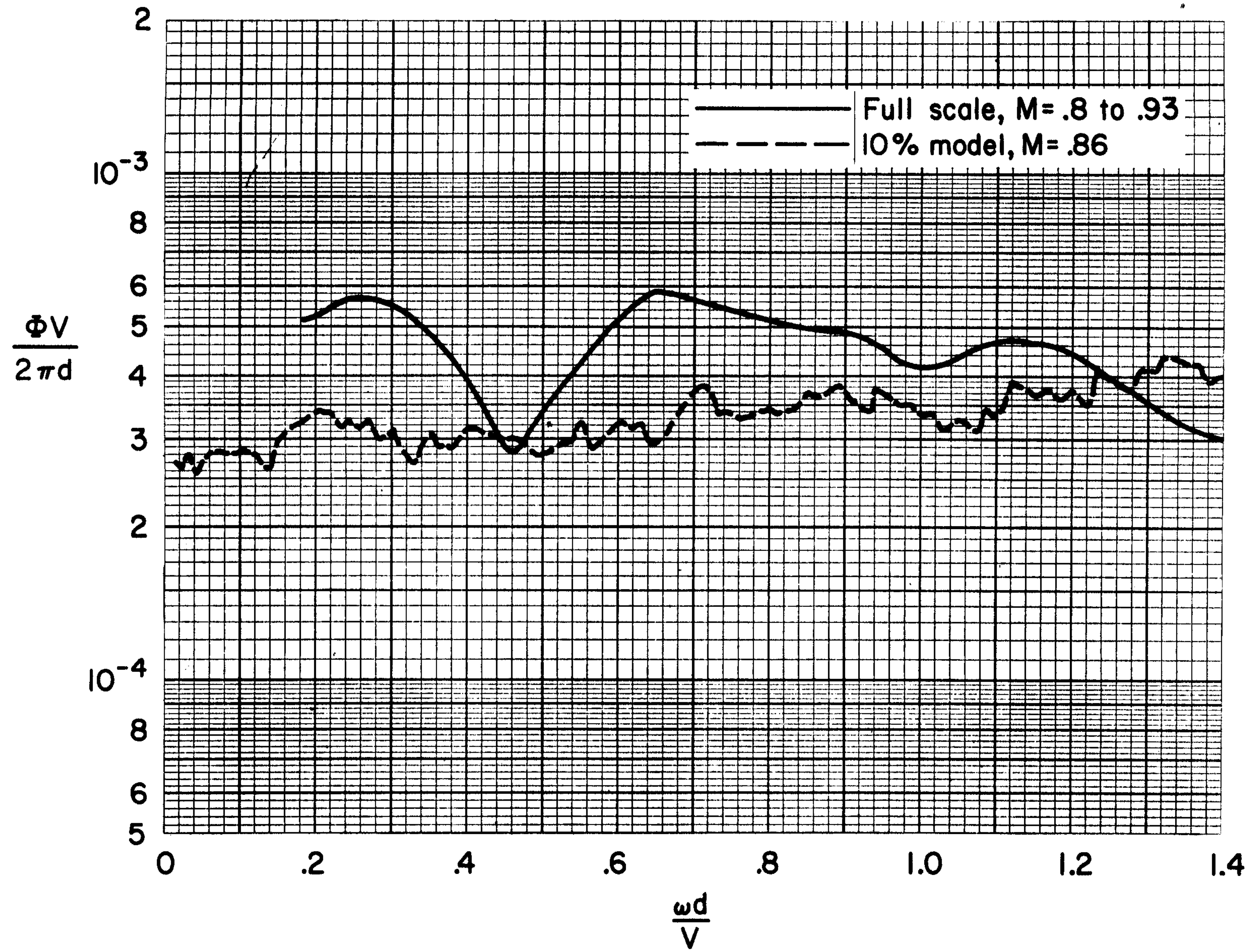


Figure 4.- Time history of pressure fluctuations on the Mercury-Atlas adapter.



(a) Agena sta. 249.

Figure 5.- Power spectra of differential pressure fluctuations on the Agena with the Ranger 5 payload.



(b) Agena sta. 259.

Figure 5.- Concluded.

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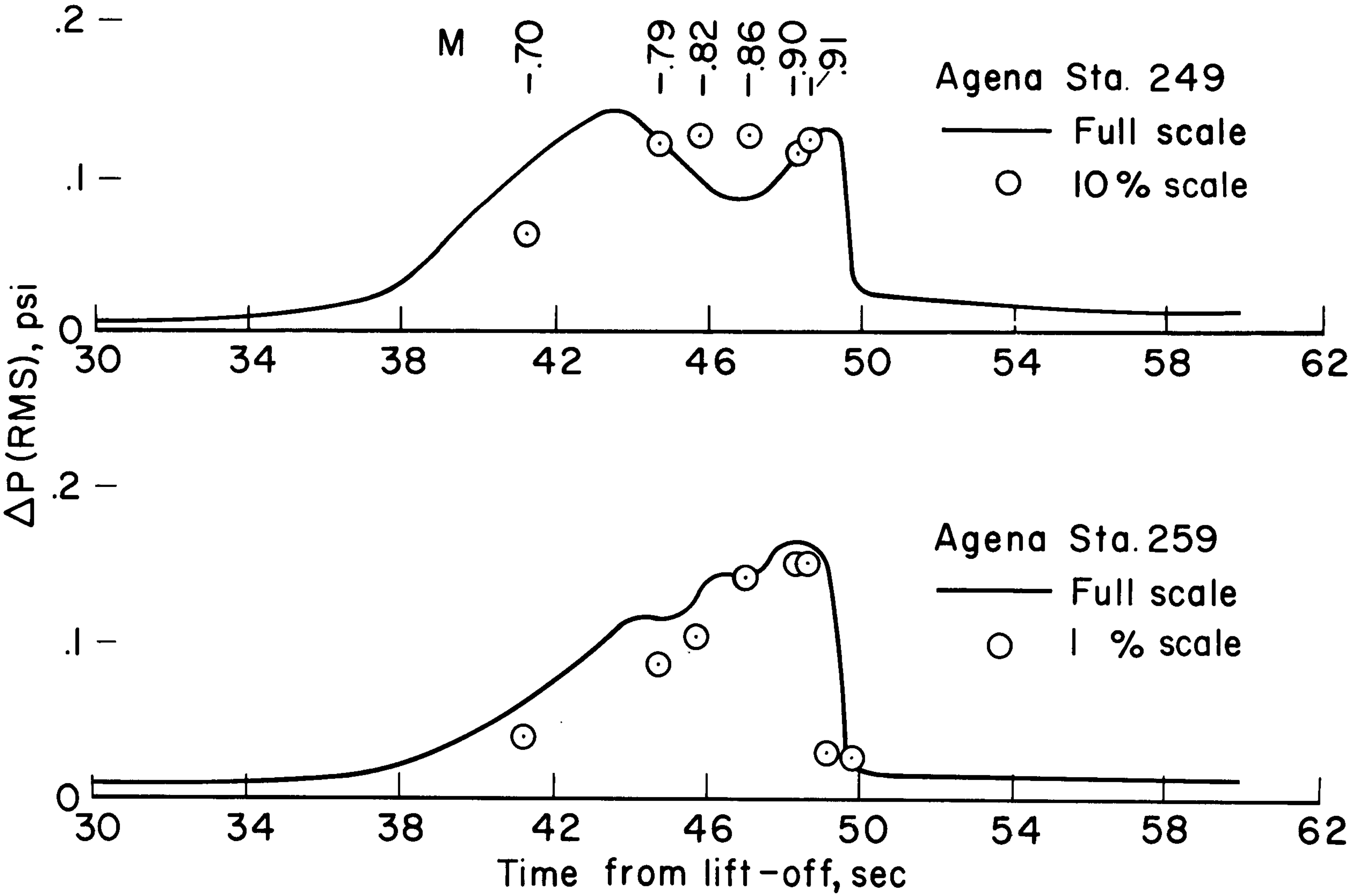

Figure 6.- Time histories of differential pressure fluctuations on the Agena with the Ranger 5 fairing.

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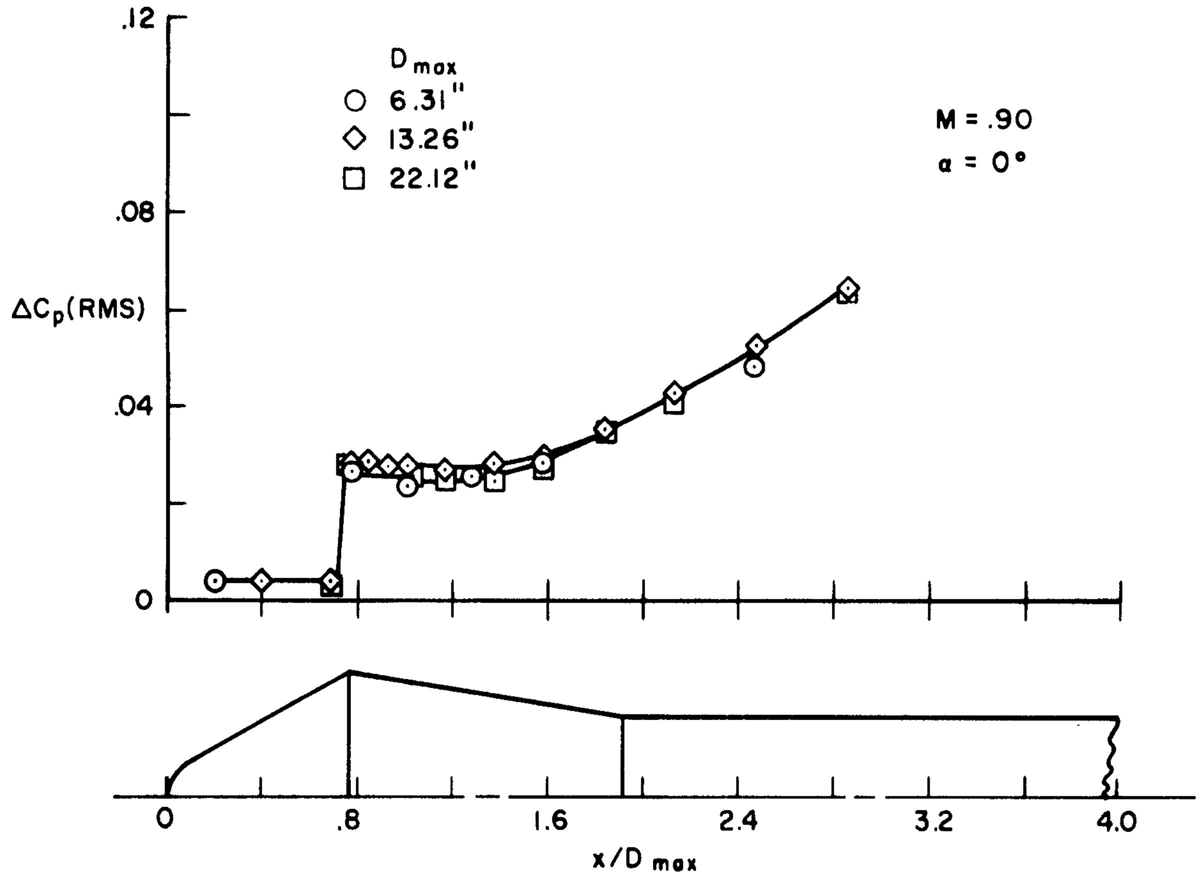

Figure 7.- Effect of scale on model 8 pressure fluctuations.

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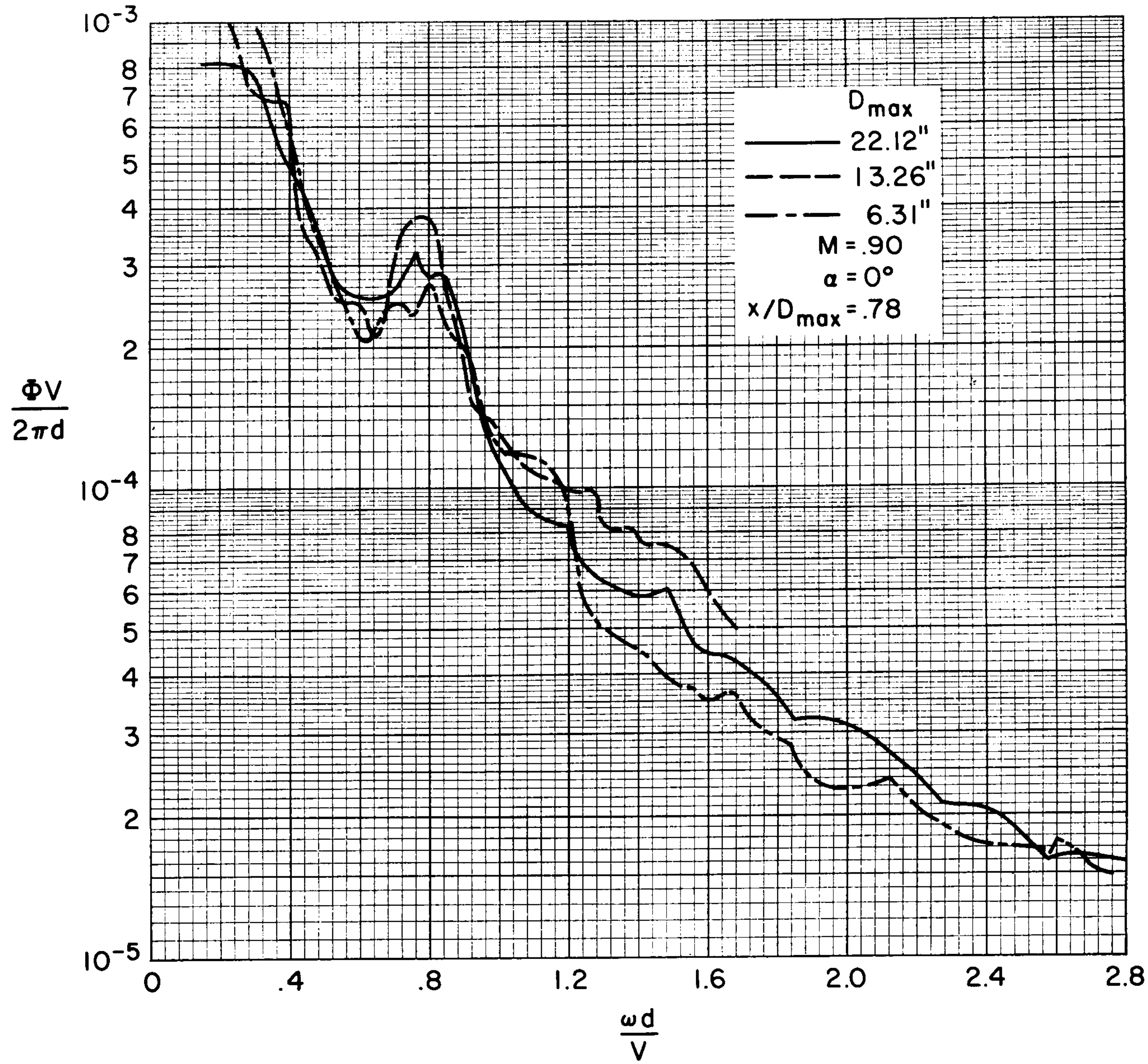

Figure 8.- Power spectra of pressure fluctuations on model 8.

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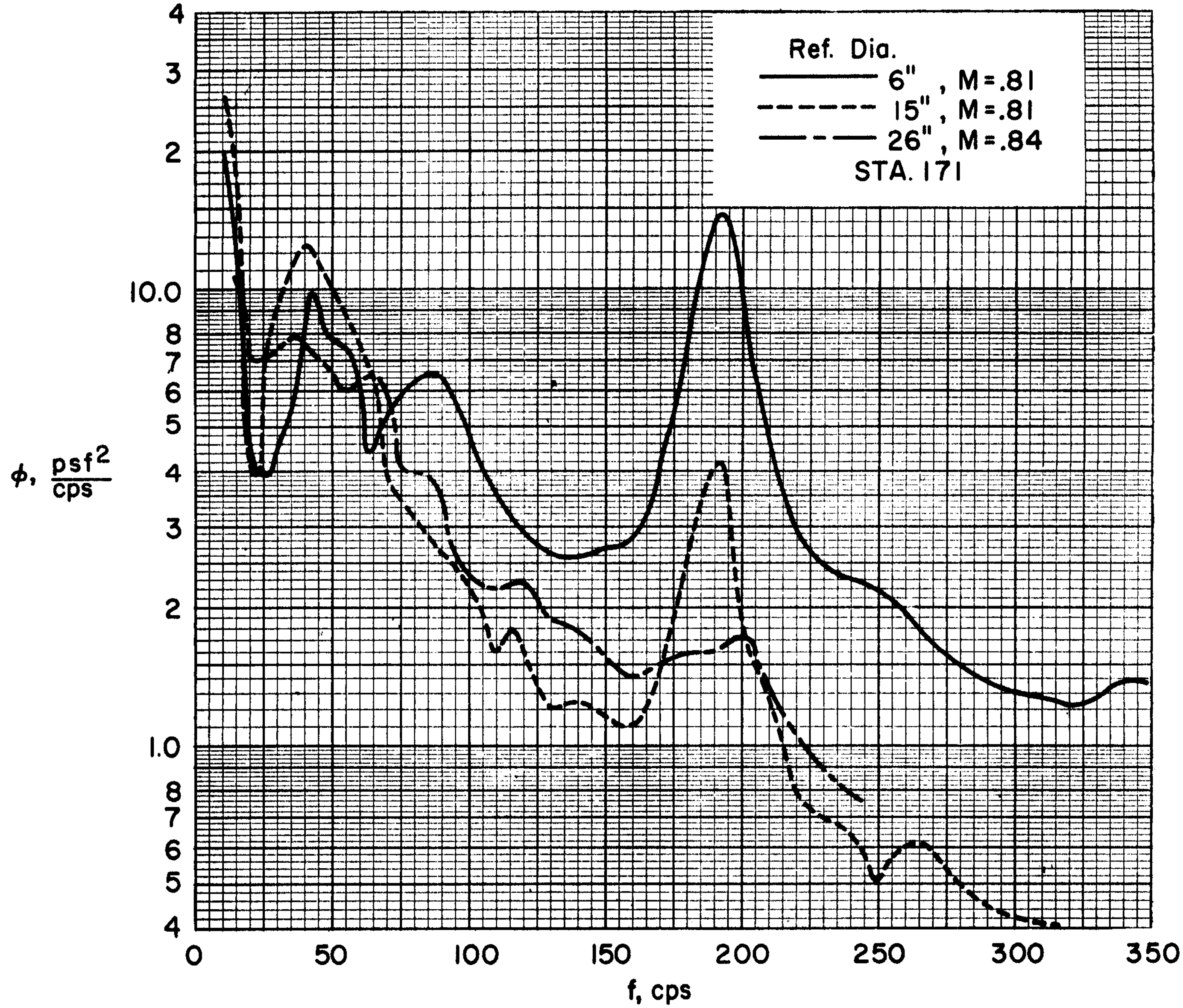

Figure 9.- Model 13a power spectra in region of a shock wave.

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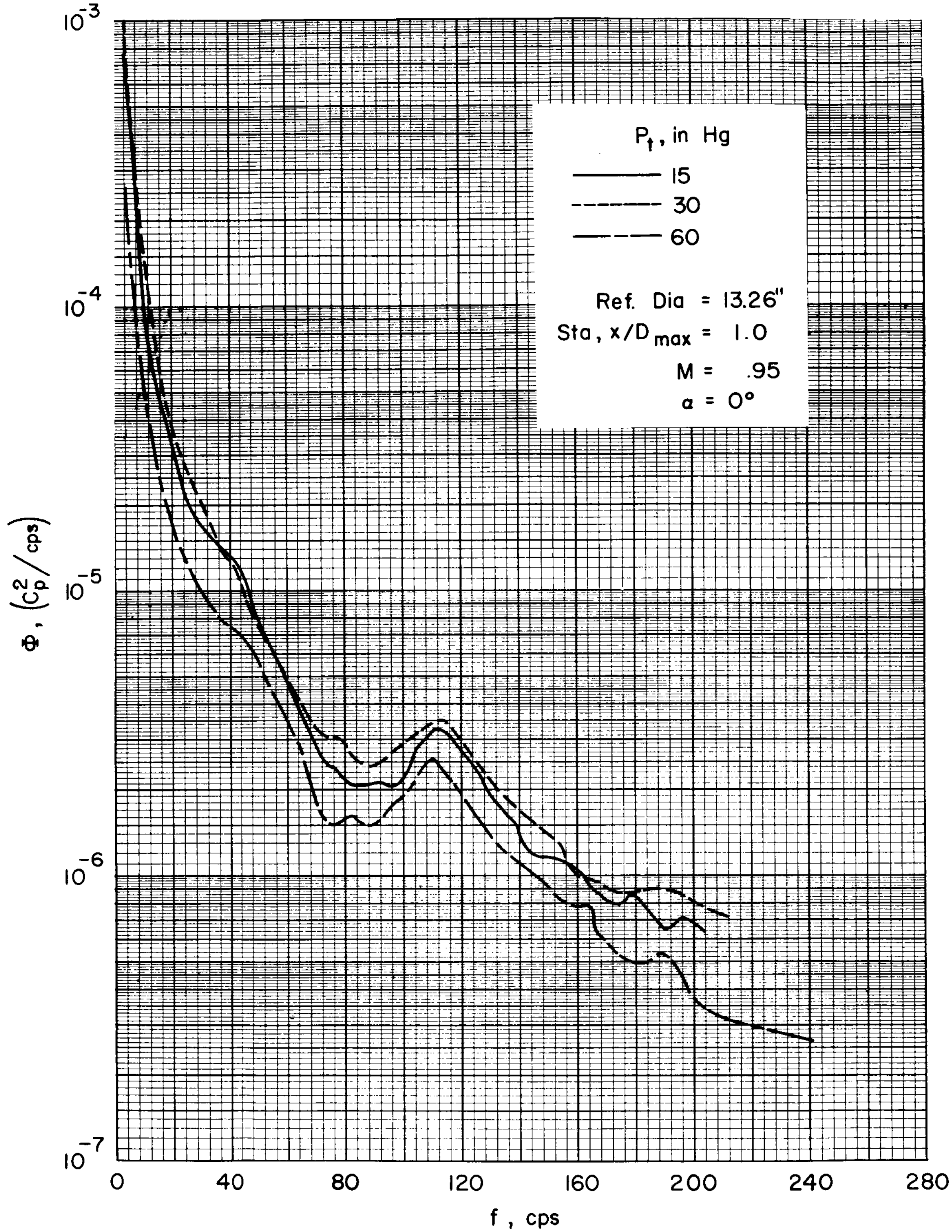

Figure 10.- Effect of total pressure on power spectra of differential pressure fluctuations on model 8.

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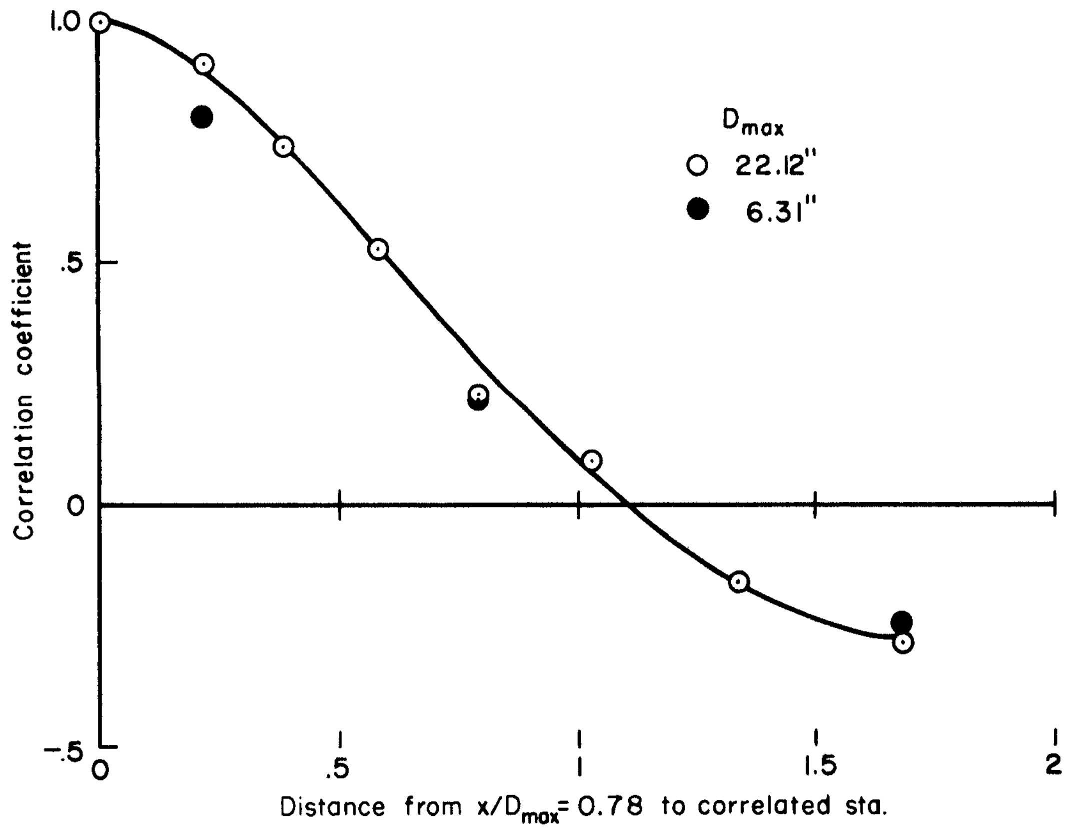

Figure 11.- Longitudinal correlation of pressure-fluctuation measurements on model 8.

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